RESEARCH NOTE

Hydraulic Effects on Ultraviolet Disinfection: Modification of Reactor Design

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ABSTRACT: Results from several recent studies of UV disinfection of reclaimed wastewater led to the conclusion that disinfection effectiveness is likely to be reduced at low flow velocities. Considerations from basic hydraulics make this likely because the formation of boundary layers along wetted surfaces in lamp banks reduces the UV dose absorbed by most of the water. Boundary layers grow thicker with decreasing mean flow velocity through the lamp bank. This analysis of disinfection is supported by two reports of hydraulic tests and a study that changed flow rates to change the estimated dose per bank of lamps and found that the proportion of viruses killed in each bank was independent of flow velocity over the observed range. Additional laboratory and computational work is suggested to test this hypothesis. If, as expected, results confirm the hypothesis, then arrays of small vanes, similar to those used in aeronautical engineering, may provide a useful countermeasure. This recommendation can be tested by the same methods used to test the hypothesis. *Water Environ. Res.*, **71**, 114 (1999).

KEYWORDS: ultraviolet, disinfection, reclaimed wastewater, hydraulic effects.

Introduction

For a conventional UV disinfection system with lamps aligned parallel to the flow, it is typically accepted that reclaimed wastewater moves through it in a close approximation to ideal plug flow. Hydraulic measurements (e.g., Anderson and Tchobanoglous, 1995, and Blatchley et al., 1995) appear to confirm this because Morrill Dispersion Indices (MDIs) in dye tracer studies in Orange County, California, were close to the expected value of one for plug flow and Blatchley et al. observed that lamp arrays in their experiment smoothed out an initially nonuniform velocity distribution. However, basic hydrodynamic considerations (e.g., Currie, 1974, and Iranpour et al., 1997) imply that boundary layers are present close to all wetted surfaces, which in disinfection units include the bottom and sides of the channel and the lamp sleeves; Blatchley et al. observed a boundary layer near the bottom of their channel, which was the only wetted surface near which their measurements were made. Moreover, boundary layers are expected to become thicker at lower average velocities.

These considerations appear to provide a framework for understanding results recently reported by Jolis and Hirano (1993), who observed a large apparent departure from first-order disinfection kinetics when they attempted to increase the UV dose to tertiary effluent by decreasing the flow rate. The fraction of bacteria or viruses killed per lamp bank was nearly independent of estimated doses. However, their dose estimation method, based on a formula supplied by the manufacturer of their equipment, Trojan Technologies, Inc., London, Ontario, Canada, did not take boundary-layer effects into account. The formula was

$$Q \times D = 1\,344 \times \exp(0.026\,3 \times \%T) \qquad (1)$$

Where

Q = discharge,
D = dosage, and
$\%T$ = percentage of transmittance.

Because lamp intensity is fixed, the dose of UV is proportional to exposure time for each volume element of water as long as the average distance from the volume element to nearby lamps does not change significantly. In turn, the exposure time is assumed to be inversely proportional to flow rate. Changing boundary-layer thicknesses would destroy the simple assumption of proportionality because flow in boundary layers is slow and elsewhere is faster.

Because channels of different sizes have been used in different experiments but lamp spacings and lamp lengths are the same, results must be compared using the average flow velocity among the lamps, obtained by dividing the flow rate by the effective cross-sectional area. This gives the velocity that would be present in the absence of boundary layers. This comparison shows that the Blatchley et al. experiment was conducted at the same velocities as in some of Jolis and Hirano's measurements, despite the large difference in channel sizes and absolute flows. Thus, from Blatchley et al., one has direct experimental observation of a boundary layer several centimeters thick to support the proposed explanation of anomalous disinfection results. We also find evidence for the hypothesis in small deviations from plug flow in the Anderson and Tchobanoglous report because the deviations are consistent with the hypothesis.

As treatment plants are likely to handle a wide range of flow rates, it is desirable that disinfection behavior at low flow rates be consistent with behavior at higher flow rates. In the last part of the paper we describe experimental and computational studies to verify the hypothesis and suggest a simple way to maintain plug flow near wetted surfaces at low average velocities.

Background Studies

Jolis–Hirano Effect. The first-order kinetic model of UV disinfection (Qualls and Johnson, 1985; Scheible, 1987; and Severin et al., 1984) assumes that the probability that any microorganism will be inactivated by a UV photon is independent of the probability for any other microorganism and is proportional to the intensity of irradiation. Thus, the microorganism concentration decreases exponentially with the UV dose D, which for an average intensity I and an exposure time t is the product of I and t. In short, for N_0 (the initial concentration), $N(D)$ the concentration after an exposure D, and a proportionality constant k, $D = I \times t$ and $N(D) = N_0 \exp(-kD)$.

Scheible explains how previously observed departures from this simple idealized model are successfully explained by the shielding provided by larger waste particles and other effects in real wastewater instead of a suspension of free-floating microorganisms. Many papers report observing satisfactory approximations to first-order kinetics or to the modified model when UV disinfection is applied to secondary effluent. The principal model other than first-order kinetics is an empirical multiple linear regression on logarithms of parameters of the disinfection unit and the wastewater (Emerick and Darby, 1993). Because the calculation simply finds the hyperplane that best approximates a collection of points in a multidimensional space, this procedure involves no assumptions about underlying mechanisms. These models are the foundation of methods for designing practical disinfection systems to meet regulatory standards (Loge et al., 1996), which has been shown to be feasible only in the last few years (Darby et al., 1993). However, when Jolis and Hirano (1993) tested UV disinfection on tertiary effluent in San Francisco, California, using a wide range of flow rates to vary the estimated dose, they observed an apparent independence of disinfection from the estimated dose per lamp bank so that disinfection depended only on the number of banks through which the water passed. This is different from anything previously reported.

Even though Jolis and Hirano apparently believed that their results represented a real departure from first-order kinetics, the strong support for first-order kinetics from theory and previous experiments makes it more attractive to hypothesize that first-order kinetics remains valid on microscopic scales but that some unconsidered phenomenon produced the macroscopic results of this experiment.

As noted in the introduction, boundary-layer effects along wetted surfaces provide the most plausible hypotheses to explain the results once one observes that "high-dose" observations correspond to relatively low average flow velocities upstream and downstream of lamp banks, as shown in Table 1. These velocities and those in the following sections are calculated outside the lamp banks to avoid the disturbing effects of lamps.

Near wetted surfaces, viscous effects have increased importance; thus in regions that are well away from solid surfaces, the local velocity is above the mean for all of the fluid. The difference implies that most of the water does not flow close to surfaces, which has three consequences. First, the reduced effective cross-sectional area increases the velocity of flow; second, the higher velocity reduces the water's exposure time; and third, the average distance from the lamps to the region of most rapid flow is also larger than one would expect from uniform plug flow, so that the intensity is decreased. Thus, departures from plug flow reduce the dose and hence the effectiveness of disinfection for most of the water. Enhancement of these effects with decreasing flow velocities would account for the apparent dose-independence of disinfection in this type of experiment, which might reasonably be called the Jolis–Hirano effect.

Table 1—Average flow velocities using equation 1.

Single bank dose, mW·s/cm²	Flow, gpm	Flow, L/s	Velocity outside lamp banks, cm/s
27.0	95.5	6.0	26.7
32.0	80.6	5.1	22.7
37.0	69.7	4.4	19.6
44.0	58.6	3.7	16.4
48.0	53.7	3.4	15.1
53.0	48.6	3.1	13.8
61.0	42.3	2.7	12.0
76.0	33.9	2.1	9.3
95.5	27.0	1.7	7.6

Huge Channel Study. Support for reasoning in the previous section is provided by examination of the experimental results reported by Blatchley et al. (1995). This paper includes a valuable theoretical study of the intensity distribution along a lamp and was written to convince environmental and civil engineers to perform pilot tests of UV disinfection on a scale that is intended to allow boundary and end effects to be little more important than they are in operational-scale systems. Accordingly, Blatchley et al. used for their horizontal lamp test a 64-lamp array in a channel 60 cm wide filled to a depth of 60 cm, as shown in Figure 1. The figure shows that this was larger than the lamp arrays used by others. Blatchley et al. used flows of 6.1×10^3 and 7.6×10^3 m^3/d (1.6 and 2.0 mgd), which would be full-scale operation or nearly so for many wastewater treatment plants in smaller medium-sized communities.

Figure 2 shows that hydraulic conditions for large arrays are similar to those of smaller arrays in Figure 1. This is further verified from velocity measurements by Blatchley et al. that show that boundary-layer effects at average flow velocities are in the same range as in Jolis and Hirano (1993) measurements.

Two sets of measurements were taken along vertical lines at the centerline of the channel. Thus, effects of the sides could not be observed. In one set of data, measured with the horizontal lamp array, the average velocity was ~19.5 cm/s; these data show barely a hint of slowing in the measurement closest to the bottom at a height of ~4 cm. The other measurements with vertical arrays of lamps had an average velocity of ~9.7 cm/s; at this velocity the bottom boundary layer is more than 5 cm thick. These two average velocities evidently are close to the velocities estimated in Table 1 for Jolis and Hirano's estimated single-bank doses of 37 and 76 mW·s/cm^2, respectively. Thus, at single-bank doses between these two values, which include the majority of Jolis and Hirano's measurements, one must infer boundary layers several centimeters thick along the channel bottom and the sides and the lamp sleeves. This is a significant fraction of the lamp spacing.

Orange County Hydraulic Study. This report is a discussion

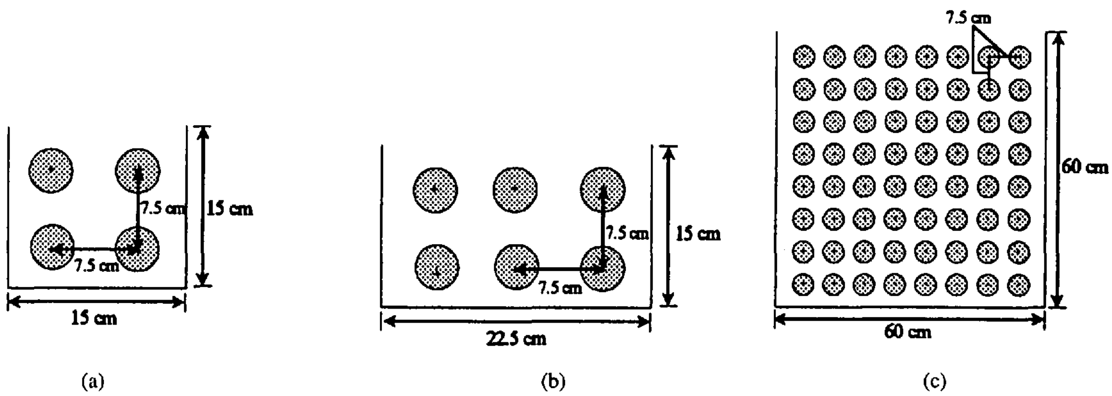


Figure 1—Cross sections of lamp arrays used in different experiments: (a) from Loge et al. (1996) and Jolis and Hirano (1993), (b) from Anderson and Tchobanoglous (1995), and (c) from Blatchley et al. (1995).

of the authors' experimental procedure and results and provides readers with an extensive summary of the general methodology of hydraulic testing. They conclude that, despite some departures from uniformity, the Trojan UV 2000 (Ontario, Canada) pilot-scale disinfection system operated with a satisfactory approximation to plug flow. However, their discussion of hydraulic testing provides the information necessary to show that results are consistent with the hypothesis of substantial boundary-layer effects at low flow velocities. Their flows of 230 and 450 L/min (60 and 120 gpm) correspond, respectively, to velocities of 11.2 and 22.4 cm/s in the interval used by Jolis and Hirano (1993).

Experiments were conducted by injecting a fluorescent tracer to the water. All measures of the hydraulic characteristics of the UV 2000 are derived from the curves of dye concentration as a function of time (F-curves) or their derivatives, residence time distribution (RTD) curves. Key parameters are (a) Morrill Dispersion Indices derived from the F-curve, implying plug flow if $1 <= \mathrm{MDI} <= 2$; (b) the theoretical residence time T, computed from the flow rate and channel volume; (c) the mean residence time θ, computed from the RTD curve; (d) the time of the peak of the RTD curve t_p, counted from the beginning of the dye injection; and (e) the median of the RTD curve t_{50}, also from the beginning of injection.

Anderson and Tchobanoglous (1995) explain that these parameters were originally developed for studying settling basins, where three particular ratios have simple physical meanings: $\theta/T < 1$ implies dead space, $t_p/\theta < 1$ and $t_{50}/\theta < 1$ indicate short circuiting, and $\theta/T > 1$ is impossible if T is calculated from the correct volume but underestimating the volume may easily occur in an open-topped channel in which head loss produces a depth gradient. As some of their measurements include $\theta/T > 1$, this apparently happened.

The authors assert that there is little or no dead space or short circuiting in a UV reactor: therefore, they interpret their results more generally as indicating nonuniform flow. However, flow with boundary layers approximates both short circuiting and dead space. Thus, the boundary-layer hypothesis predicts that $t_p/\theta < 1$ and $t_{50}/\theta < 1$ for all measurements of the UV channel. Out of a total of 18 sets of measurements (two dye injection modes, three banks, and three flow rates) $t_p/\theta < 1$ in 16 of the 18, $t_p/\theta = 1$ in one, and $t_p/\theta = 0.91/0.90$ in the last case, which probably is not significantly greater than 1 (t_{50}/θ is less than one in all measurements).

We find additional evidence for the boundary-layer hypothesis in measurements of the head loss in each lamp bank. Head loss should decrease with the square of velocity, but the observed decline is a little slower. This is consistent with a reduction of the effective cross-sectional area with thickening boundary layers.

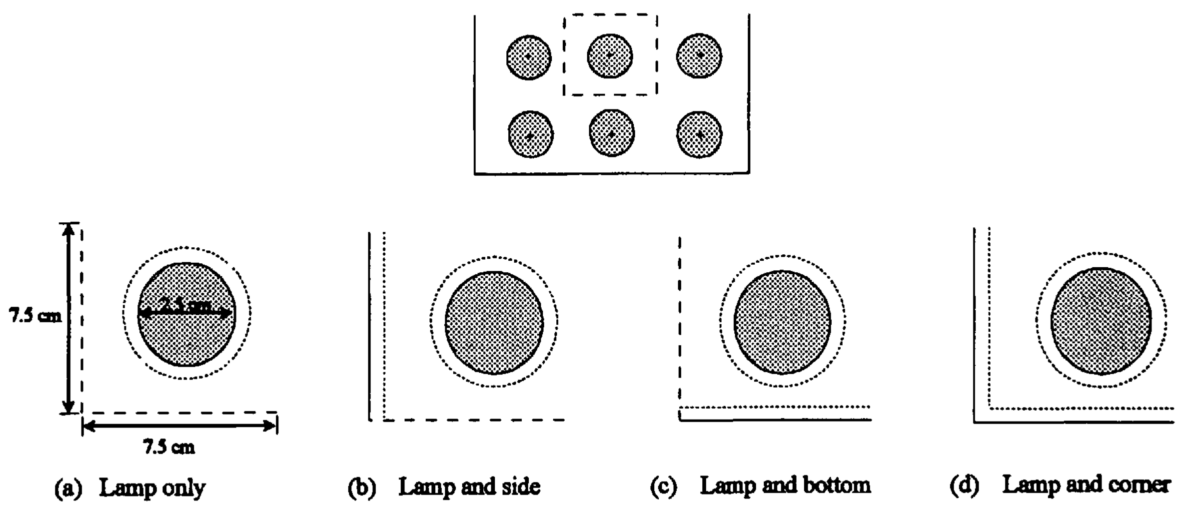


Figure 2—Cross-sectional views of simplified boundary-layer configurations.

Table 2—Effective area after reduction by boundary layer, based on Figure 2.

Boundary-layer thickness, mm	Effective area, cm^2		
	Lamp only	Lamp and one side	Lamp and corner
0.00	51.34	51.34	51.34
2.50	49.18	47.30	45.49
5.00	46.63	42.88	39.38
7.50	43.68	38.06	32.94
10.00	40.35	32.85	26.35
12.50	33.62	27.24	19.43

Discussion

Laboratory Studies. Several laboratory studies are desirable to clarify and test the hypothesis and conclusions drawn from research reports discussed in the previous section. The first step is to attempt to replicate the results of Jolis and Hirano (1993) at one or more suitably equipped wastewater treatment plants in other places. Another obvious study is to extend the hydraulic study of Anderson and Tchobanoglous (1995) to other velocities. If it is feasible to sample regions near the surfaces, using thinner tubes than those in the sampling apparatus in Anderson and Tchobanoglous, then comparing *F*-curves and RTD parameters from such samples to the ones in their report might be beneficial. Other chemical and biological analyses of water in boundary layers also appear desirable.

Based on the strength of the present evidence for boundary-layer effects at low flow velocities, a tentative approach has been formulated to reduce these effects by attaching small angled vanes to the sides and bottom of the channel and the lamp sleeves. If these computational tests are sufficiently successful, both hydraulic and disinfection tests will be needed.

Computational Studies. Laboratory fluid dynamic studies of UV lamp arrays in more detail than studies like those in Anderson and Tchobanoglous are possible, but they are likely to be expensive. It is likely to be more cost effective to seek further insight to fluid flow in lamp arrays by a computational simulation because software that can support such studies on workstations or high-end personal computers is now widely available and relatively inexpensive.

Software such as MACSYMA PDEase™ (MACSYMA Inc., Boston, Massachusetts) will now perform volume decomposition and numerical calculation in a finite element computation of a partial differential equation or will offer a preliminary decomposition that the user can modify.

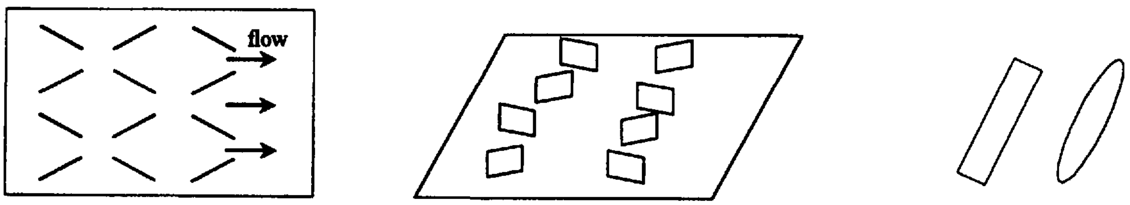
For the calculations needed to explore the basic hypothesis about the effect of boundary layers, the calculation would be relatively simple because the channel would be rectangular and one could begin by merely including cylindrical voids in the water volume to represent the lamps. The elements would be smaller near the wetted surfaces to provide higher resolution of the flow there, and the sizes and shapes of the elements might be adjusted to the input flow velocity because of the changing thicknesses of the boundary layers.

Simulation at this basic level of approximation could test the validity of the basic concept of boundary layers, which is depicted in Figure 2. The spacing among the lamps and between the lamps and the channel boundaries allows any cross section through any bank in any of the channels in Figure 1 to be subdivided so that each lamp is surrounded by a square that is 7.5 cm on a side. Then the area not occupied by the lamp is $(7.5)^2 - \pi(1.25)^2$ cm$^2 \approx 51.35$ cm^2. Table 2 shows the available area if a static layer of specified thickness exists around the lamp alone or around the lamp and one or two sides of the square to represent the effect of a side and/or the bottom of the channel. This binary division of the area into static and freely flowing regions is only a schematic depiction of the actual situation in which continuous gradations occur, but it provides easily calculated values for possible degrees of deviation from the assumption of plug flow extending to all wetted surfaces and may be useful to compare with the results of computational simulations and laboratory tests.

A relatively simple simulation with the lamps as cylinders also would provide comparisons between small and large channels and between arranging the banks in a straight configuration, as Anderson and Tchobanoglous (1995) did, or in a serpentine configuration, as was used by Jolis and Hirano (1993) and by Loge et al. (1996).

Additional realism in a computational simulation would be provided by including more detailed depictions of the disinfector. The supports at the ends of the lamps are an obvious additional item and another is the baffle plate in the inlet box of the system used by Anderson and Tchobanoglous (1995). Simulating the effect of this plate could check the validity of Anderson and Tchobanoglous's interpretation of their data. They attributed most of their evidence of nonuniform flow to lingering effects of the baffle.

Angled Vanes to Enhance Plug Flow. Although the studies described in the previous section are desirable to verify the boundary-layer hypothesis, the evidence for it appears sufficiently strong now that it seems worth considering a possible modification of conventional UV reactor design to counteract the formation of boundary layers. The aircraft industry has long used arrays of



(a) Top view of vanes (b) Perspective elevation view of vanes (c) Possible cross sections for a vane, flat or curved sides

Figure 3—Example of vane array for plug flow enhancement (not to scale).

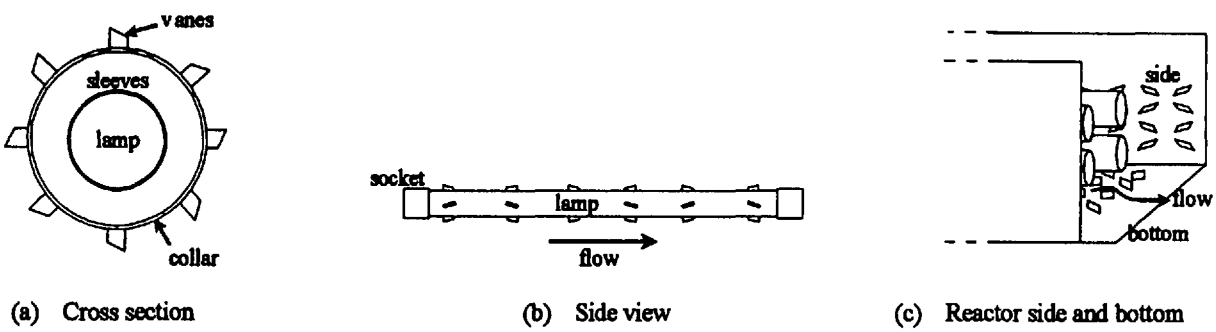


Figure 4—Example of vane array on lamp and reactor (not to scale).

small vanes strategically located on wings to control the formation of boundary layers. By setting the vanes at small angles to the flow, as shown in Figure 3, angled alternately left and right, areas of widening and narrowing cross section are formed that respectively decelerate and accelerate the flow, thus interfering with the uniformity of motion needed for boundary-layer formation.

Applying the same approach in a UV reactor, something like that shown in Figure 4c would result, with vanes attached to the sides and bottom of the channel. Small collars with vanes can also be fabricated easily to snap onto or slip over the quartz lamp sleeves as indicated in Figures 4a and 4b. Testing different configurations and optimizing parameters are other tasks that should be done by computation.

The typical approach to optimization is of course to formulate some function of the parameters of the design that is to be optimized, where the function expresses the benefit or value of the design, and maximize the benefit function or, equivalently, to minimize a function representing harm or penalty. In the case of UV reactors, one wants to minimize the extent to which real disinfection performance deviates from the ideal of inverse proportionality between flow and dose. However, because of the complexity of necessary finite element calculations, it is not clear that the deviation from ideal flow can be evaluated at tolerable computational cost with sufficient accuracy to support a conventional minimization algorithm seeking minimal deviation as a function of the vane parameters. Instead of a provable local or global minimum of a deviation function, it may be necessary to accept a configuration that is merely satisfactorily better than a naive adaptation of aeronautical vane arrays.

Conclusion

Dealing with variations in disinfection effectiveness caused by hydrodynamic effects at low flow rates appears to be an issue that deserves more attention than it has received from researchers studying UV disinfection of reclaimed wastewater. Comparing the papers reported by Jolis and Hirano (1993), Blatchley et al. (1995), and Anderson and Tchobanoglous (1995) has led to the conclusion that boundary-layer effects significantly reduce the effectiveness of UV disinfection with decreasing flow velocities. We recommend further laboratory and computational studies to verify these conclusions and examine the phenomenon in more detail. If these studies produce the results expected, it may be possible to use small arrays of vanes to counteract the formation of boundary layers, as is already applied to aeronautical engineering in aircraft design. This approach may be tested using computational and laboratory studies similar to those recommended for testing the boundary-layer hypothesis.

Acknowledgments

Credits. The authors thank K. Ludwig, A. Magallnes, K. Flaig, and J. Wilson, J. Crosse, and J. Langely of the City of Los Angeles' Bureau of Sanitation Management for support and comments. Thanks are also due to professors D. Miller, M. Stenstrom, and G. Tchobanoglous for their guidance and reviews.

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Submitted for publication April 2, 1998; accepted for publication June 3, 1998.

The deadline to submit Discussions of this paper is May 15, 1999.

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